

Predicting the Stress-Strain State of the Fractured Rock Massif on the Example of Interchamber Pillars

Vladislav Trifonov, Ivan Emelyanov, Viachslav Sinegubov

Abstract: The article describes the finding of the qualitative differences in the formation of the stress-strain state of a disturbed rock massif on the example of interchamber pillars with various methods of accounting for the structural disturbance and different spatial geometry of the cracks. Three numerical models are created with different methods of accounting for the disturbances in the massif continuity: in the first model, the strength of the massif is described by the Hoek and Brown criterion; the second and the third models are rock massifs for which violations in the continuity are formed explicitly, using ready-made templates of the systems of cracks presented in the Phase2 software product. The results obtained for the different models illustrate the inaccuracies occurring in assessing the disturbance of rock massif using score criteria. Models with underrated strength properties of the rock inaccurately describe the real mechanisms of the fractured massif: the qualitative description is not consistent with the results of field observations and geological surveys of rocks in general.

Keywords: Interchamber Pillar; Stress-Strain State, Rock Massif, Fracturing; Continuity Breach; Crack.

I. INTRODUCTION

The fundamental point in studying a fractured rock massif is the presence of uncertainty of boundary conditions, namely epistemologic uncertainty, which is primarily a consequence of insufficient knowledge about the processes and the structure of the fractured massif and results in replacement by some idealized geomechanical models in studying the real rock massif. Since the knowledge of the natural processes will always be incomplete, the epistemologic uncertainty will also always be present; with that, it is characterized by the following: its relation with the system of knowledge that meets the current level of human development — accurate and required at the present stage of scientific development, i.e., the achieved level of development does not allow obtaining additional information required for removing uncertainty. The cumulative effect of the massif fracturing parameters and the strength of the rocks it consists of determine the stability and the nature of massif destruction [1-5]. The analytical [6-9] and empirical [10, 11]

methods of determining the stability of underground workings and chambers used for designing them do not always allow considering explicitly the fracturing parameters. The study was aimed at identifying the qualitative differences in the formation of the stress-strain state (further referred to as SSS) of fractured rocks on the example of interchamber pillars with the use of various ways of considering the structural fracturing. The main task of the study was disclosing the substantial inaccuracies of the formation of the rock massif SSS, where fracturing was assessed by the rating criteria. To solve this task, three numerical models with different methods of considering the irregularities in the rock massif continuity were created in the Phase2 application. It should be noted that the paper considers only the strain inside the pillar, since at the moment, there are no quantitative or qualitative methods of assessing the zone of pillar effect on the rock massif above or below, and there is no stability criterion, which could be used for assessing the destruction of the pillar. The issues of analyzing the boundary stress state and methods of predicting the SSS of the rock massif around underground construction facilities were considered in [12-20].

II. PROPOSED METHODOLOGY

A. The geomechanical model of a pillar in a fractured rock massif

This paper considered a part of the rock massif where the strength and deformation properties of the ore the pillar consisted of considerably exceeded the properties of the rock layers above and underneath. The situation was considered, in which the entire model (the rock layers above and underneath, and the ore body) was penetrated by a single system of cracks. The physicomaterial properties of the rock above the ore body were the following: $\sigma_{comp} = 56.9 \text{ MPa}$; $\nu = 0.11$; $E_{str} = 27.65 \text{ HPa}$; $\gamma = 24 \text{ kN/m}^3$; those of the rock below the ore body were: $\sigma_{comp} = 101.6 \text{ MPa}$; $\nu = 0.12$; $E_{str} = 49.79 \text{ HPa}$; $\gamma = 25 \frac{\text{kN}}{\text{m}^3}$; and those of the ore body were: $\sigma_{comp} = 256 \text{ MPa}$; $\nu = 0.08$; $E_{str} = 85.45 \text{ GPa}$, $\gamma = 26 \text{ kN/m}^3$. The depth of the ore body was 500 m, its thickness was 8 m. The parameters of the cracks system were as follows: a system of cracks with small spacing between the cracks, the cracks were slightly rough, the rocks were wet, moderately weathered, the cracks were oriented relatively favorably, the angle of the cracks was 20° to the vertical, the density of the cracks was 10 cracks per meter. The problem was considered in a flat setup: it was assumed that only the pressure from the overlying rock mass was acting, which was 12 MPa applied at the height of 8 m from the ore body.

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In the first model created in this work, the strength of the massif was described by the Hoek and Brown criterion. The second and third models presented solid rock, for which violations of the rock massif in the model were explicitly generated using the ready-made templates of the systems of cracks shown in the Phase2 software product.

The models were created using the Phase2 software product, in which the finite element method was implemented, which was widely used for solving geomechanical tasks [21-27]. The fracturing was explicitly considered by separating the elements of the finite element grid in the mathematical model into separate blocks. The mechanisms of stress and strain were different for the elements within the block and for the interacting elements of adjacent blocks, which was the model of fracturing within the continuous medium theory, where the stress and strain distribution function was continuous. A similar approach to resolving the problems of geomechanics is widely used in the engineering practice [28-34]. The change in the main maximum stress inside of the pillar is assessed for pillars with a width between 4 and 12 m with increments of 1 m.

In the second and the third model, the strength of the rocks was described by the Mohr-Coulomb theory, and the strength at the contact of the cracks — by the nonlinear Barton-Bandis parameters. The difference between the second and third models was in the spatial location of the cracks relative to each other: in the second one, the structural disturbance is presented by a parallel system of cracks, while in the third — by an isogonal system of cracks.

For studying the occurring stresses, parallel (Fig. 1 a) and isogonal (Fig. 1 b) systems of cracks were explicitly modeled. The mean distance between the lognormally distributed cracks for the parallel system of cracks was adopted as 0.1 m, the angle of incidence was 70°. Creating similar boundary conditions for the model with isogonal system of cracks causes a number of difficulties associated with the spatial location of cracks relative to each other in the presence of two or more intersecting systems of fractures, since the rating of rock massif, according to the RMR classification of Benyavsky, considers the location of cracks relative to each other exclusively by the distance between the cracks. It is adopted that an isogonal system is a parallel system of cracks with the average spacing between the cracks equal to one meter, and the angle of incidence of 52°, which is intersected by a secondary parallel system of cracks with the average distance between the cracks of one meter, which is perpendicular to the main parallel system of cracks; after destruction of the walls of the cracks, the

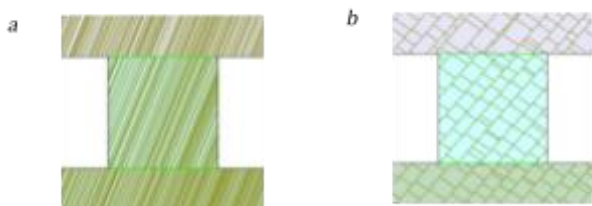


Fig. 1. The models of fracturing given explicitly; a — a parallel system of cracks (the second model); b — an isogonal system of cracks (the third model).

phenomenon of residual strength is observed. The effect of the relative position of the cracks relative to each other on the formation of the picture of the rock massif SSS was studied based on the above-mentioned second and third models with various types of crack systems specified explicitly by modifying one of the basic fracturing parameters — the angle of incidence. Pillars of various cross-section shapes were considered: extruded vertically with the width of 6 m; square — 8 m; and horizontally elongated — 10 m. The angle changed in the range of [0°; 90°] with the increments of 15°, other boundary conditions remained unchanged. In solving the problems of geomechanics, the mountain range is the main object of the study. As the result of developing the underground space, the stress state is redistributed in the rock massif, therefore, the mandatory condition of geomechanical research is obtaining complex data about the stresses, the structural indicators, and the properties of the host rocks and the rock massive itself [35]. This issue is fundamental and is considered in resolving any practical geomechanical problem [36-39].

For modeling, the primary size of the pillar is to be determined. For this purpose, the method of the All-Russian Research Institute of Mining Geomechanics and Survey for calculating the dimensions of pillars in chamber systems of nonferrous metal ores development was used. The general form of expressing the condition of pillars strength, based on the Turner-Shevyakov's principle, is written as follows:

$$\frac{k_l k_a \gamma H S}{S_p} = \frac{\lambda k_{ph1} k_{ph2} k_{pr} \sigma_{comp}^0}{k_z}$$

The left part of the condition is the load on the pillar, the right one is its strength.

It is adopted that the width of the studied area is equal to the depth ($L = 500$ m), the ore body is placed horizontally, the pillars have a square cross-sectional shape, are located on a square grid, and the chamber width is $b = 12$ m. Based on the adopted placement of the grid of pillars, the strength condition takes the following form:

$$\frac{k_n k_a \gamma H (a + b)^2}{a^2} = \frac{\lambda k_{pr} \sigma_{comp}^0}{k_z} \left(0.6 + 0.4 \frac{a}{h} \right),$$

where a is the sought width of the pillar. The calculation scheme is shown in Fig. 2. Resolving this equation allows setting the primary width of the pillar in the adopted geological conditions and the geometry of the mined area. According to the adopted parameters, the sought width of the pillar is 11 m.

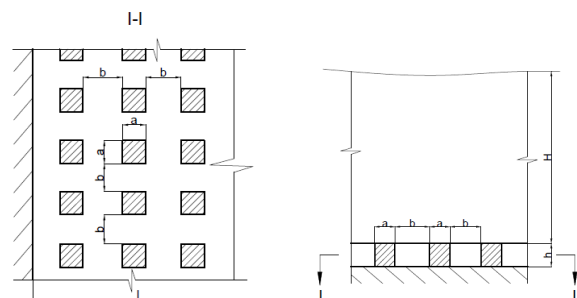


Fig. 2. The calculation scheme of determining the initial dimensions of the pillars using the methods of the All-Russian Research Institute of Mining Geomechanics and Survey

B. Calculating the parameters of interchamber pillars with the use of geomechanical numerical models

The first studied model is the model of continuity disruption that considers decreased strength properties of the rocks the massif consists of by the RMR rating of the rock massif. The mechanical behavior of the massif is described by the Hoek and Brown criterion:

$$\sigma_1 = \sigma_z + \sigma_{c,i} \left(m_b \frac{\sigma_3}{\sigma_{c,i}} + s \right)^\alpha$$

The rock quality designation (RQD) and the value of the GSI parameter, respectively, were defined by the following ratios:

$$RQD = 100e^{-0.1\lambda}(0.1\lambda + 1);$$

$$GSI = RMR - 5.$$

where $\lambda = 10 \text{ pcs/m}$ was the cracks frequency. For the adopted source data, the coefficients of the massif strength reduction m_b and s were calculated (it should be noted that in the Phase2 software, parameter σ_1 is not used). These coefficients, along with the Benyavsky's classification rates are shown below (Table 1). Below are some typical curves of SSS formation in pillars (Fig. 3).

Table 1. Parameters of a rock massif rating and the Hoek and Brown criterion in the model of a solid massif

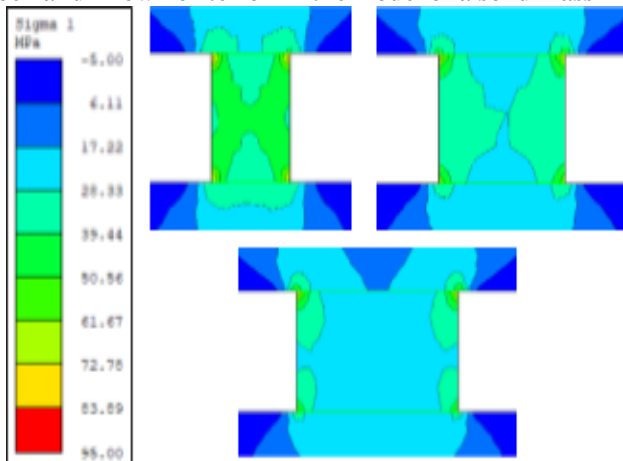


Fig. 3. The curves of the maximum strain in the pillars of the first model of various shapes; a – elongated vertical, five meters wide; b – square, eight meters wide; c – elongated horizontally, 11 m wide.

The second and third models represent the solid rock in which fracturing is modeled explicitly. In this case, the strength of the rock is described by the Mohr-Coulomb criterion:

$$\tau = \sigma \tan \varphi + C,$$

and the strength of cracks along the contact — by the nonlinear Barton-Bandis parameter:

$$\tau = \sigma_p \tan \left(JRC \cdot \lg \frac{JCS}{\sigma_p} + \varphi_r \right).$$

The normal and tangential stiffness was calculated using the elasticity and shear modulus, respectively:

$$k_n = \frac{E_i \cdot E_m}{L(E_i - E_m)};$$

$$k_t = \frac{G_i \cdot G_m}{L(G_i - G_m)}.$$

The data about the strength and deformation properties of the rock and the cracks are shown below (Table 2).

Some typical curves of strain formation in the pillars for the second and the third models are shown in Fig. 4 and Fig. 5, respectively.

Table 2. Parameters of rocks and cracks strength criteria

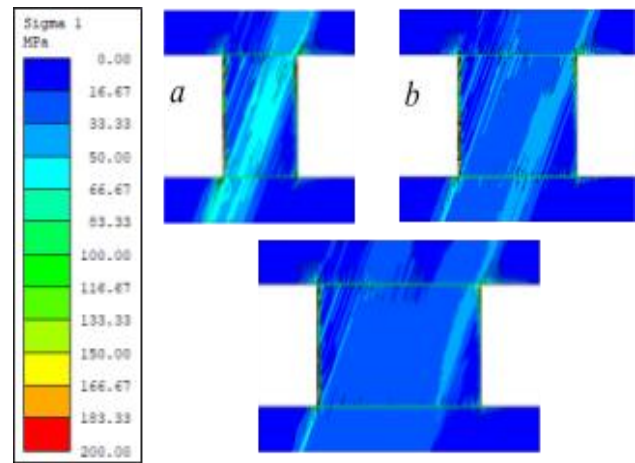


Fig. 4. The curves of the maximum strain in the pillars of the second model with a parallel system of cracks of various shapes; a – elongated vertical, five meters wide; b – square, eight meters wide; c – elongated horizontally, 11 m wide.

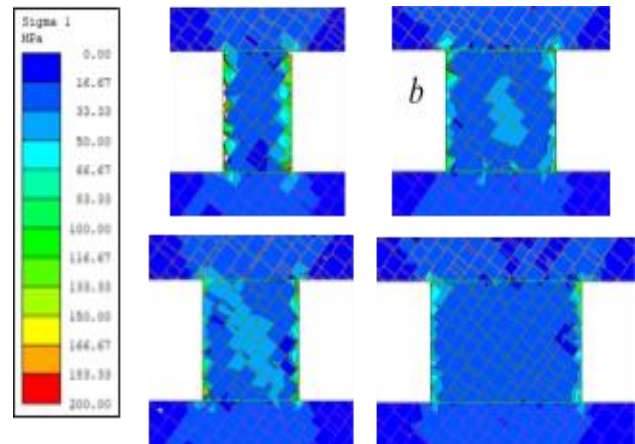


Fig. 5. The curves of the maximum strain in the pillars of various shape in the third model with the isogonal system of cracks; a — elongated vertically, five meters wide; b — elongated vertically, five meters wide; c — square, eight meters wide; d — elongated horizontally, 11 m wide.

The effect of the angle of incidence on SSS formation in a pillar, depending on the angle of incidence of systems of cracks for the second and third studied models, is shown in Fig. 6 and Fig. 7, respectively.

III. RESULTS ANALYSIS

For the first model (Fig. 3) the direction of forming the zones of strain concentration remains qualitatively constant upon changes of the pillar width in the entire range: the zones of concentration take the characteristic hourglass shape. For the parallel system of cracks (Fig. 4),

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the areas of strain concentration and their development upon reducing the width of the cross-section differ significantly from the picture of strain in the first model: the zones of increased strain generally lie between the cracks

intersecting the corners of the pillar, and in the zones outside these cracks, the strain remains almost unchanged, except for local increases in individual cracks.

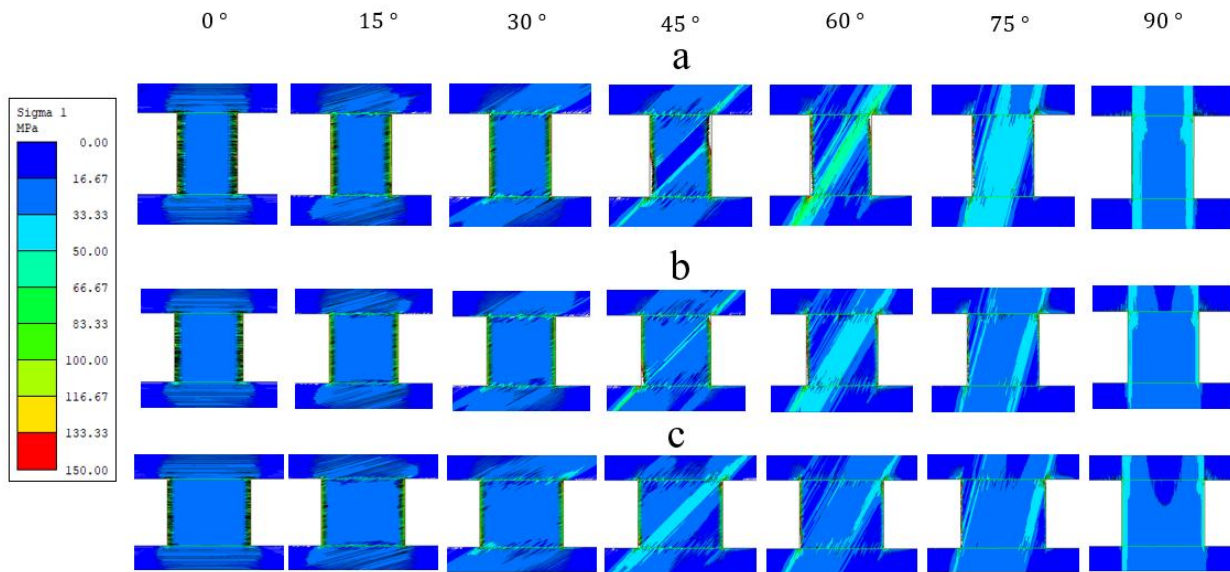


Fig. 6: The curve of the main maximum strains distribution in the pillars of the second model, depending on the fracturing angle; a — elongated horizontally pillar six meters wide; b — square pillar eight meters wide; c — elongated horizontally pillar 10 m wide

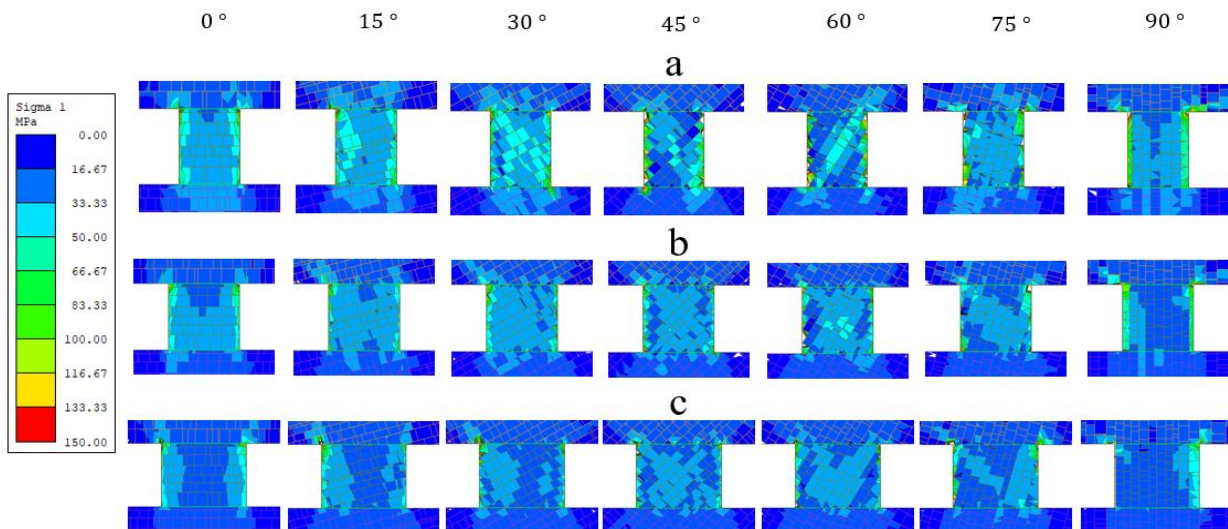


Fig. 7. The curves of the main maximum strains distribution in the pillars of the third model, depending on the fracturing angle; a — elongated horizontally pillar six meters wide; b — square pillar eight meters wide; c — elongated horizontally pillar 10 m wide.

In the model with an isogonal system of cracks (Fig. 5), same as in the first model, the symmetry of strain distribution can be traced relative to the vertical axis of the pillar, except for the pillar with the width of seven meters (Fig. 5 b), and the width of eight meters (Fig. 5 c). Such areas of strain concentration strongly contradict the pattern of strain distribution in the first model, in which the strain increases in the direction “from sides to the center.” In other pillars, the strain distribution can be considered conditionally uniform: the zones of concentrations in them are at the extreme sides blocks of the rock.

Upon strain distribution, in the center of pillars of various width of all three models (Fig. 8 a), the following conclusions can be drawn: since in the pillars with the width

greater than the height, the strains have identical values, in using various methods of modeling the structural disturbance, the boundary conditions are chosen correctly. Besides, consideration of the fracturing through lowering the strength characteristics of the massif should be used if the width of the pillar is greater than its height. In turn, the differences of strain in the center of the pillar (Fig. 8 a), and the differences of the greatest strains along the horizontal cross-section of the pillar (Fig. 8 b) for various models upon reducing the width of the pillar speak of individual consideration of each particular case: the strains are distributed in various patterns, and almost do not match quantitatively.

Explicit modeling of fracturing will allow better assessment of the nature of pillar destruction: since destruction primarily occurs along the contact of the cracks, the stability of the pillars depends on the spatial orientation of the cracks relative to each other. This approach will ensure lower losses of mined ore by reducing the size of the pillars when possible. In the scoring systems for assessing fracturing, the effect of the angle of inclination on changes in SSS will not have a qualitative effect on the strain pattern, but will only change the quantitative values. This approach does not describe the reality. The areas of strain concentration of the second model (Fig. 6) change their distribution after changing the angle of inclination of the fracturing. In the third model (Fig. 7) the areas of strain concentration change their location and the covered area in a less ordered manner than in the second model. The areas of strain concentrations do not appropriately follow the changing angle of inclination of the fracture. Such changes are caused by the fact that more complex spatial geometry of the location of the cracks in the system of elevated strain in the zone will not strictly dominate in only one group of cracks, but will greatly depend on the spatial geometry of their location relative to each other. The qualitatively very different formation of the areas of strain concentrations results in different strain values, at which the pillar loses stability, as well as in different zones of primary deformations and, consequently, zones of destruction.

inside the pillars stretches horizontally, i.e., with the width of the cross-section exceeding the height of the pillar itself, has similar distribution pattern for all considered models: the zones of strain concentrations are formed, resembling the hourglass shape characteristic of the laboratory samples. This similarity should rather be considered to be the inaccuracy of creating the model: with increasing the size of the considered zone, the scale effect becomes more significant. In general, the scale effect will reduce the similarity between real objects and the laboratory samples and increase the anisotropy of the massif properties. On the other hand, despite this similarity of strains, since the most important task is reducing the dimensions of the pillars and, consequently, reducing the loss of minerals during mining, it is necessary to determine the nature of pillars destruction and the preceding SSS in the rock massif more accurately.

IV. DISCUSSION

The consistent study of this problem starts with studying the strain inside the pillars. The results obtained for various models illustrate the inaccuracies arising in assessing the disturbance of the solid rock with score criteria: the model with low rock strength properties quantitatively describes the real mechanisms in a fractured array with a significant error, while the qualitative description is not consistent with the data of field observations and geological studies of solid rock in whole. The fact that the used methods, despite the imperfection of the studied models, can describe and control the destruction and deformation mechanisms is evidence of the appropriateness of their use. However, this leads to significant errors and inaccuracies in the forecasts, which affects the rational use of the subsoil.

Further development of the technology of developments and geomechanics as a science, in general, requires moving to more detailed and complex models than those in which lowered strength properties of the rock sample are used. Criteria need to be introduced that would allow considering the spatial geometry of the slackening surfaces inside the solid rock and moving away from the concept of the continuous medium to the description of the massif with consideration of the continuity violations. One of the main problems is also obtaining reliable data about the rock massif: it is necessary to improve and create new methods of exploration, laboratory tests and tests in situ, processing the obtained data, and field observations

V. CONCLUSION

Further research studies in the field of the mechanics of solid deformable body destruction are planned within the framework of the discrete media mechanics. This will require refining the geomechanical model, determining the joint effect of the massif around the pillar on the pillar itself for various boundary conditions, such as the ratio of the strength and deformation properties of the massif and the pillar, the conditions of the pillar contact with the rock above and below the pillar, etc. One should move from considering a flat task to the three-dimensional one, consider the tectonics, seismic loads, and the anthropogenic factors that influence strain redistribution.

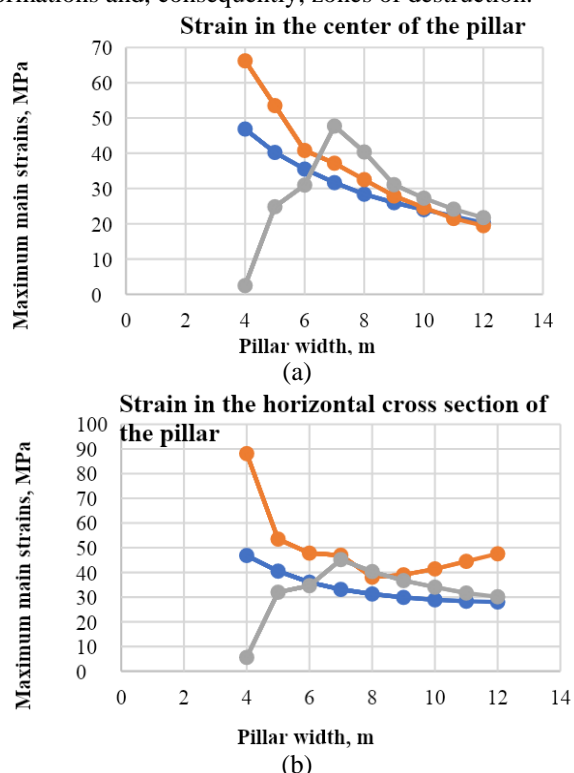


Fig. 8. The dependence of strain at various points of pillars in different models; a — the first model; b — the second model; c — the third model

Assessment of the identified qualitative differences in the formation of strain, strain concentration zones, and their changes for different models depending on various parameters shows a clear need for creating numerical methods of calculation and for stability criteria for interchamber pillars dimensions. On the one hand, the strain

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The pillar – roof – soil system should be qualitatively and quantitatively studied to determine the zone of pillar effect on the surrounding rock massif, set new and more sophisticated criteria and conditions of the stability of interchamber pillars.

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